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THEORETICAL STUDIES GROUP
CONTRIBUTIONS TO THE 14TH
INTERNATIONAL COSMIC RAY
CONFERENCE, MUNICH,
AUGUST 1975

JULY 1975

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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CONTENTS:

MOLECULAR HYDROGEN IN THE GALAXY AND GALACTIC GAMMA RAYS

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Estimates made of column densities of H_2 at $\ell^{II} = 0^0$ indicate that H_2 is far more abundant than HI in the inner galaxy and is the key to an explanation of the γ-ray observations. This is also reflected in the correlation of galactic longitude and latitude distributions of γ-rays and molecular clouds. Particularly strong evidence is found from the galactic survey of CO emission at 2.64 mm. The cosmic-ray distribution inferred from the calculations is not uniform but only weakly dependent on the total gas distribution in the inner galaxy.

1. Introduction. Molecular hydrogen has long been suspected to be an important component of interstellar gas because it is the most stable low-temperature form of the most abundant element in the galaxy. H_2 is expected to be the predominant form of hydrogen in cool clouds of sufficient density. However, despite its abundance, it is difficult to measure its galactic distribution directly. Results from two promising methods for indirectly studying the galactic distribution of H_2 are discussed here, viz., recent galactic surveys of 100 MeV γ-radiation and 2.6 mm radio line emission from the $J = 1 \rightarrow 0$ transition of CO molecules. To these surveys, which reflect the extent and distribution of H_2 in the plane of galaxy, we will add corroborating information on the amount and latitude distribution of gas in the direction of the galactic center supplied by X-ray, optical, and infrared absorption measurements.

2. The Recent SAS-2 Gamma-Ray Galactic Longitude Observations. Fichtel et al. (1975) have recently reported the results of a sky survey made of 100 MeV γ-rays using a spark chamber aboard the SAS-2 satellite. The similar galactic longitude distribution observed by the OSO-3 detector was also noted to be distinctly uncorrelated with the 21 cm distribution by Clark et al. (1970). The OSO-3 result implied an increase in cosmic-rays, unseen gas or both in the inner galaxy, and it was suggested by Stecker (1969, 1971) and Stecher and Stecker (1970) that molecular

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hydrogen unseen in 21 cm surveys could account for a large part of the γ-ray
enhancement in the inner galaxy. A model has been proposed by Bignami and Fichtel
(1974) and Bignami et al. (1975) based on producing large enhancements at the
locations of arms mapped by 21 cm surveys by postulating higher gas densities than
are seen in 21 cm and proportionately higher cosmic-ray intensities in the arms.
However, Burton et al. (1975) indicate that the arms outside of 25^{0} from the galactic
center are optically thin in 21 cm and significantly higher amounts of HI in the arms
than those deduced in previous surveys appear to be ruled out. We, therefore, feel
that the galactic γ-ray observations can be better understood by using other
observations in addition to 21 cm surveys to determine the role of H_2 clouds invisible
in 21 cm emission.

3. The Galactic CO Distribution and the Molecular Ring at ∼5kpc. A survey of the
galactic longitude distribution of CO emission in the galactic plane has recently
been made by Scoville and Solomon (1975). The importance of this survey in under-
standing the distribution of H_2 in the galaxy lies in the fact that CO is an
excellent tracer of H_2.

Scoville and Solomon (1975) have used the velocity profile data obtained in
their CO survey in conjunction with the Schmidt (1965) rotational model of the
galaxy to determine the mean distribution of CO in the galaxy as a function of
galactocentric distance for distances greater than 2.6 kpc. This distribution
shows a broad peak with a maximum near 5 kpc which they have concluded indicates a
ring of H_2 clouds in this region. The general form of the molecular cloud distribution
obtained by Scoville and Solomon has recently been confirmed in an independent CO
survey by Burton et al. (1975). The connection between this feature and the γ-ray
emission ring at ∼5 kpc (Puget and Stecker, 1974) led to the suggestion that the
γ-ray data also provide evidence for the molecular cloud ring near 5 kpc (Solomon
and Stecker, 1974). Coincidently, there is also a similar distribution and peak
in the giant HII regions of the galaxy (Metzger 1970). This may be understood to
be the effect of hot young stars in OB associations being formed out of dense
molecular clouds in this ring. The formation of such a prominent molecular ring
poses an intriguing problem for galactic structure theory.

4. Molecular Hydrogen and Total Column Densities in the Direction $\ell=0^{0}$. Various
methods can be used to estimate the amount of gas in the direction of the galactic
center (Stecker et al. 1975). The results are summarized in Table 1.

Table 1. Column Densities of Hydrogen at $\ell = 0^{0}$ Excluding the Galactic Nucleus
         ($\times 10^{-22}$) (cm^{-2}) $(N_{G.C.,\odot})$

$<N_{HI}>$ from 21 cm radio	∼0.6 to 1.5	Daltabuit and Meyer (1972)
	1 to 2	Kerr and Westerhout (1965)
	∼1.2	Clark (1965)
$<2N_{H_2}>$ from CO	3 to 10	Scoville and Solomon (1975)
$<2N_{H_2} + N_{HI}>$ from SAS-2 γ-ray flux	∼(11.5±2)	This work ($I_{CR} \gtrsim I_{\odot}$)
$<2N_{H_2} + N_{HI}>$ from X-ray absorption	6.5 to 9	$\sigma_{H_2}/2\sigma_{HI} \leq 1.7$ (Kaplan and Markin 1973) as verified by the measure- ments of Crasemann et al. (1974).
$<2N_{H_2} + N_{HI}>$ from IR absorption	5 to 7.5	Ryter, et al. (1975)

Scoville, Solomon and Jefferts (1974) estimate the total mass of the molecular disk near the galactic center to be

$$4 \times 10^7 \lesssim (M_{GC}/M_\odot) \lesssim 10^8$$

This yields an estimated flux from π^0 decay in the range

$$0.6 \times 10^{-5} \lesssim \Delta I_{\gamma, GC} \lesssim 1.5 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1}$$

which is only about one tenth of the observed flux at $\ell = 0^\circ$.

5. Galactic Gamma Ray Flux as a Function of Longitude. In performing numerical calculations of the longitude distribution of the galactic γ-ray flux from π^0 decay, we have used the survey of Scoville and Solomon (1975) to obtain the relative distribution of molecular hydrogen in the galaxy as a function of galacto-centric distance $\tilde{\omega}$ and have normalized to a total column density of 7×10^{22} cm^{-2} in the direction of the galactic center using the X-ray and infrared absorption measurements (Table 1) which are consistent with, but presumably more accurate than the column densities deduced from the γ-ray or CO results. The contribution from atomic hydrogen was estimated based on the numbers given by Kerr and Westerhout (1965) and Westerhout (1970).

For the purpose of the calculations to estimate the effect of cosmic ray enhancements in the galaxy, it was assumed that such enhancements may be correlated with the gas distribution so that

$$\frac{J(\tilde{\omega})}{J_\odot} = \left[\frac{n_{HI}(\tilde{\omega}) + 2n_{H_2}(\tilde{\omega})}{n_{HI,\odot} + 2n_{H_2,\odot}} \right]^\alpha \qquad (7)$$

The results are shown in Figure 1 for $N_{GC,\odot} = 7 \times 10^{22}$ cm^{-2} and $\alpha = 0.3$ corresponding to an increase of about a factor of 2 in the cosmic ray flux in the 5kpc region as indicated by studies of the supernova remnant distribution in the galaxy (Ilovaisky and Lequeux 1972, Kodaira 1974) and the synchrotron radiation measurements (Daniel and Stephens 1975). This corresponds to a mean value for the total gas density of ~ 1 atom/cm^3 at 10 kpc of which ~ 40 percent is in molecular form. This agrees with the values given by Spitzer, et al. (1973) from measurements of rotational UV absorption lines of H_2 and those given by Jenkins and Savage (1974) for Lyman α lines of HI. In the 5 kpc region, this corresponds to a volume-averaged total density of ~ 5 atoms/cm^3 of which ~ 80 percent would be in molecular form.

The results of the numerical calculations are shown in Figure 1 together with the flux distribution given by Fichtel et al. (1975) from the SAS-2
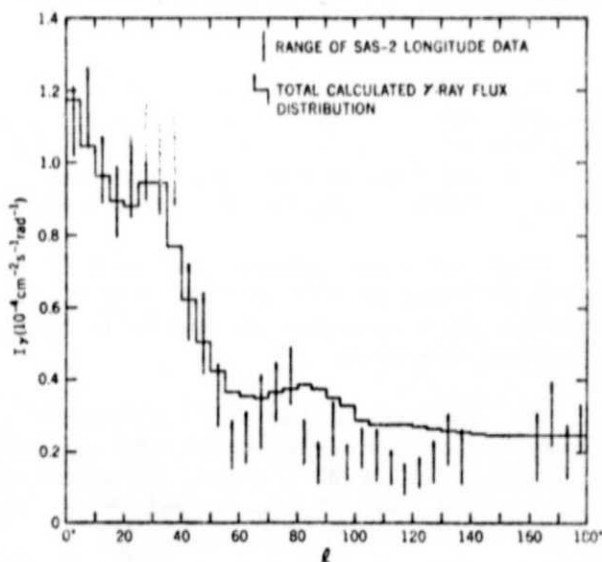
Figure 1. Comparison of the total calculated γ-ray flux distribution with the SAS-2 longitude data.

observations for the half-plane from 0° to 180° over which the CO measurements of Scoville and Solomon (1975) can be applied. Effects of secondary electron production, bremsstrahlung and Compton interactions are included. These results indicate that most of the observed γ-ray enhancement at low longitudes is primarily a result of increased gas density and that the molecular ring near 5 kpc plays an important role in accounting for this increase.

Cosmic rays are limited to a small variation over the galactic disk given by $0.2 \lesssim \alpha \lesssim 0.5$ as derived from the limits on the amount and distribution of gas implied by the observations discussed in section 4. We thus conclude that cosmic rays cannot vary linearly with gas density over all segments of the galaxy nor do they appear to be uniformly distributed.

The results indicate that the character of the longitude distribution of galactic γ-radiation corresponds well with the overall density distribution in the galaxy implied by the CO and 21 cm measurements and that this distribution has a broad maximum in the 5 to 6 kpc region. Higher frequency modulations by spiral arms do not appear to us to play a significant role in determining the galactic γ-ray distribution within the statistical errors and 5° resolution of the SAS-2 data, at least for the half plane analyzed here using the CO data. In the other half plane, $180^\circ \lesssim \ell \lesssim 360^\circ$, three apparently sharp features have been identified by Fichtel et al. (1975) with the Scutum, Norma and "3 kpc" arm features designated in 21 cm surveys. The two inner features at 330°-335° and 340°-345° may correspond to a bifurcation of the broad moleuclar ring near 5 kpc on the other half-plane of the galaxy; the feature at 310°-315° is perhaps somewhat more puzzling since this should be associated with a correspondingly strong feature at $\ell \approx 50^\circ$ which appears to be absent in both the γ-ray and CO data. There are, however, large error bars associated with the 310°-315° observation due to the fact that the SAS-2 spark-chamber telescope only viewed this direction obliquely. Also, Puget et al. (in prep.) have indicated that large corrections due to nearby features are necessary in the 310°-360° region. Future CO observations from the southern hemisphere could help increase our understanding of the matter distribution in this region.

Thus, the galactic gas seems to have a large-scale superstructure modulated by spiral arm perturbations similar to that seen in M31 in 21 cm emission (Guibert 1974, Emerson 1974) and in our own galaxy in nonthermal radio emission (Price 1974) and it appears to be the superstructure which determines the character of the general central enhancement in the γ-ray longitude distribution.

It would also appear that in both external galaxies and our own Galaxy, the density gradient of the H_2 distribution is steeper than that of the HI distribution, resulting in a decrease in the ratio n_{H_2}/n_{HI} with distance outward from the region of maximum density.

The total contribution from bremsstrahlung and Compton interactions of both primary and secondary electrons to the galactic γ-ray flux in the central region is of the order of 30 percent, in agreement with the estimates made by Stecker et al. (1974) using the observed γ-ray energy spectrum obtained by SAS-2.

6. **Gamma-Ray Latitude Distribution and Associated Line of Sight Reddening.** In addition to the γ-ray longitude distribution measurements reported by Fichtel et al. (1975), a galactic latitude distribution was also obtained. This distribution shows an asymmetry with respect to the galactic plane with more flux coming from positive galactic latitudes in the case of moderate latitudes $6^\circ \lesssim |b| \lesssim 30^\circ$. This can be understood in the context of section 4 where it was pointed out that UV, X-ray infrared absorption measurements indicate that the total column density of gas is proportional to the reddening in a given direction and that in the direction of highly reddened objects most of the hydrogen may well be in molecular form as expected in dense dust clouds and as is indicated by only a partial correlation with 21 cm emission. The data of Knapp and Kerr (1974) in the region of the sky located between $\ell = 345^\circ$ and 30° and between $b = 10^\circ$ and 30° can be used to evaluate the average reddening and HI column density at $b = 20^\circ$. We obtain $\langle E_{B-V}(20^\circ)\rangle = 0.26$ mag and $\langle N_H(20^\circ)\rangle = 9.7 \times 10^{20}$ H atoms cm^{-2}. Postulating the same cosmic ray density as observed locally we find from the reddening and relation (2) a gamma-ray flux of 2.2×10^{-5} cm^{-2} s^{-1} sr^{-1} which compares favorably with the flux reported by Fichtel et al. (1975) observed at $b = 20^\circ$ of 2 to $2.5 \times 10^{-5} \times 10^{-5}$ cm^{-2} s^{-1} sr^{-1}. However, the flux estimated from the HI-column density is only 1.4×10^{-5} cm^{-2} sec^{-1} sr^{-1} which is particularly significant in this case because at high galactic latitudes the 21 cm emission line is not optically thick (Knapp and Kerr 1974). Thus, the situation with regard to the latitude distribution of galactic gamma-rays is analogous to that of the longitude distribution and can be better understood by taking account of H_2 unseen in 21 cm surveys of HI gas.

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INTERSTELLAR REDDENING AND GAMMA-RAY EMISSION
AS TRACERS OF INTERSTELLAR MATTER

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It is shown that the gas to dust ratio in our galaxy is the same with a very good approximation even in regions of very different densities. The detailed comparison of the latitude distribution of the γ-ray intensity with reddening data shows that in the solar vicinity the latter gives the best estimate of the total amount of interstellar gas. This conclusion is used to compute the nearby contributions to the γ-rays longitude distribution observed by SAS II and some implications for the large scale structure of the galaxy are drawn.

1. Introduction. It has become apparent in the last few years that the density of interstellar matter can deviate strongly from that of atomic hydrogen HI, as observed by its 21-cm transition line. As soon as the density reaches a few particles per cm^3, hydrogen combines to form H_2 molecules, with the fraction of atomic hydrogen left being eventually as low as a few percent of molecular hydrogen in very dense clouds (Hollenbach et al. 1971; Heiles 1975). On a large scale, the effect is able to substantially alter the picture of the gas distribution deduced solely from 21-cm observations. Fortunately, in dense regions where HI fails to be representative of the density, the column density of other elements may be high enough to make several other absorption or emission mechanisms easily observable. Among them are interstellar reddening, molecular emission or absorption, and γ-ray emission. Strictly speaking, each of these mechanisms is related to a well-defined physico-chemical species, i.e. interstellar reddening is due to dust, centimeter or millimeter absorption or emission is due to molecules (other than H_2) and γ-ray emission is produced by the interaction of cosmic rays with nucleons, that is mostly with hydrogen, be it atomic, molecular, or ionized.

II. Molecular Clouds. A typical molecular cloud can be considered as formed of a dense core, with a column density of $(5 \sim 10) \times 10^{22}$ H atoms cm^{-2} and a size of one parsec, and an extended halo, with a column density of $(5 \sim 10) \times 10^{21}$ H atoms cm^{-2} and a diameter of 10 pc or so. Typical masses are 500 $M_\odot$ for the core and 10^5 $M_\odot$ for the envelope.

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The distribution of nearby (D < 1 pkc) molecular clouds detected to date
is presented in figure 1. The survey might not be complete, but is probably
fairly representative. In figure 1, the nearby clouds located within $\sim 10^0$ from
the galactic plane are represented by small bars as a function of longitude. In
the lower part of the figure, the profiles of interstellar reddening in a
$b = \sim 10^0$ strip for distances 0.5 kpc (solid line) and 1 kpc (dotted line) of
the sun, are represented as they can be deduced from the compilation of Fitz-
gerald (1968). The correlation between the color excess and the presence of
clouds is apparent, and it can be concluded that molecular clouds are detected
wherever the color excess reaches $E_{B-V} \stackrel{\sim}{\sim} 0.4$ mag. According to eq. 1 (3), the
column density is thus $N_H = 3 \times 10^{21}$ H atom cm^{-2}. Interstellar reddening thus

appears to be a faithful
indicator of the presence
of molecular clouds, which,
in turn accommodate most
of the interstellar matter
even in moderately
obscured regions
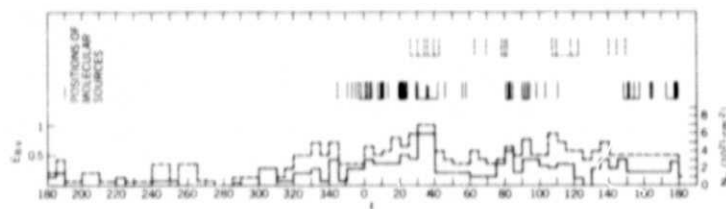(Hollenbach et al., 1971).

Figure 1. Profile of the average interstellar
reddening for distances of 0.5 kpc (solid
line) and 1 kpc (dashed line) of the sun.

III. The Gas to Dust Ratio. Interstellar matter is made of hydrogen, mixed
with a few percent (by mass) of elements with $A \geq 12$, a fraction of them being
condensed in dust. The dominant gaseous component is obviously hydrogen, but
a substantial fraction of it can be either ionized, or molecular, and thus es-
capes 21-cm detection. The only attempt to include any form of hydrogen, a
fact which may account for the large scatter in the gas-to-dust ratios found in
the literature, has been made by Jenkins and Savage (1974). In their survey,
they obtained a value $N_{HI}/E_{B-V} = 5.5 \times 10^{21}$ H atoms cm^{-2} mag^{-1}, in agreement
with most of the other measurements. They estimated that molecular and ionized
hydrogen contribute 2×10^{21} H atoms cm^{-2} mag^{-1} to reach their final value,
which applies to a region within less than ~ 1 kpc of the sun.

Gas-to-dust ratios can also be deduced in molecular clouds, where most of
the hydrogen is molecular, using the theory of excitation of molecules.
Kütner (1973) notes that in a cloud located in the Taurus complex, the formal-
dehyde molecule H_2CO observed in absorption correlates well with blue and red
extinction. From the number he quotes, one can deduce $N_H/E_{B-V} \stackrel{\sim}{\sim} (6.7) \times 10^{21}$
cm^{-2} mag^{-1}, where N_H refers to the number of H atoms, that is $N_H = 2N_{H_2}$. More
accurately, Encrenaz et al. (1975) find for carbon monoxide (CO) in emission
the ratios $N_{CO}/A_V = 1.6 \times 10^{17}$ molecules cm^{-2} mag^{-1} and $2N_{H_2}/N_{CO} = 1.3 \times 10^4$,
as soon as $A_V > 2$. With $A_V = 3.2$ E_{B-V}, we obtain $N_H/E_{B-V} = 6.6 \times 10^{21}$ H atom
cm^{-2} mag^{-1}. Finally, the x-ray absorption, which mostly reflect the column
density of M-elements (C, N, O, Ne, ...) in the line of sight, was compared to
the interstellar reddening of supernova remnants (Ryter et al. 1975). Postu-
lating universal abundances as is usual when dealing with interstellar x-ray
absorption, the value $N_H/E_{B-V} = (6.8 \pm 1.2) \times 10^{21}$ H atom cm^{-2} mag. has been
found. We adopt the value

$$N_H/E_{B-H} = 7 \times 10^{21} \text{ H atoms } cm^{-2} \text{ mag}^{-1} \tag{1}$$

IV. Gamma-Ray Emission. The galactic γ-ray background is generally believed to be due to the decay of neutral pions formed in the interaction of cosmic rays with interstellar matter. The distribution of the intensity thus reflects the product of the density of interstellar matter and that of cosmic rays. A model of the distribution of matter and cosmic rays, based on the dynamics of the Galaxy, has been proposed by Bignami et al. (1975) to account for the observed longitude distribution (Fichtel et al. 1975); following a more empirical approach, Stecker et al. (1975) suggested that the gamma-ray profile closely matches the molecular hydrogen distribution deduced from CO observations (Scoville and Solomon 1975), at least at positive longitude where a molecular emission survey exists. Further refinements have been brought by Stecker (1975), who showed that the required large scale cosmic density variation is best represented by taking it proportional to the supernova distribution in the Galaxy.

All these treatments suffer from neglecting the effect of the close-by interstellar medium, which is very patchy, and appears to introduce features which should be easily detectable with present γ-ray sensitivity. The aim of this section is to take into account the local production of γ-rays in interstellar space, that is within one kpc or so, and to evaluate the consequences on the large scale distribution.

The γ-ray intensity I_γ associated with a line of sight is given by

$$I_\gamma = \frac{1.3 \times 10^{-25}}{4} \, N_H \sim 10^{-26} \, N_H \quad (\text{ph cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}) \tag{2}$$
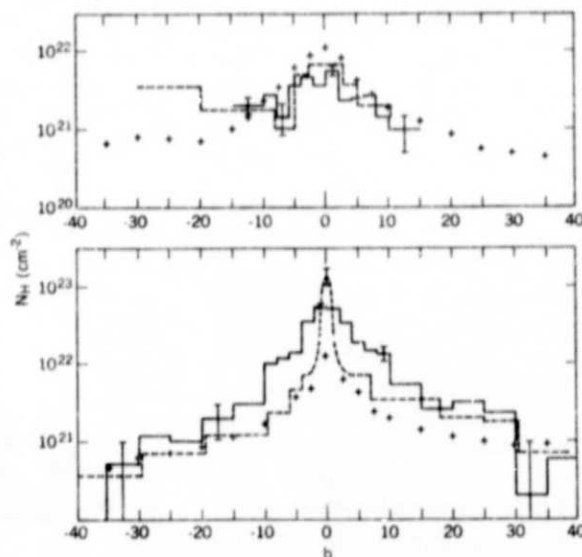
using the production rate per hydrogen atom for a cosmic-ray density equal to that observed in the solar vicinity (Stecker 1973). Using Eq. 1, this relation can be expressed as

$$I_\gamma = 7.25 \times 10^{-5} \, E_{B-V} \quad (\text{ph cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{mag}^{-1}) \tag{3}$$

In order to ease comparisons with other data, the gamma-ray intensity can be expressed through inverting eq. 2 and writing N_γ instead of N_H, i.e.

$$N_\gamma = 10^{26} \, I_\gamma \quad (\text{H atoms cm}^{-2}) \tag{4}$$

Figure 2. a upper part. Latitude distribution of γ-ray intensity (solid line), total hydrogen column density deduced from equation 1 (dashed line), and HI column density (crosses). Data are averaged over 60° in the direction of the galactic anticenter.
b. lower part. The corresponding distributions for the inner Galaxy. Data are averaged over 60° in the direction of the galactic center.
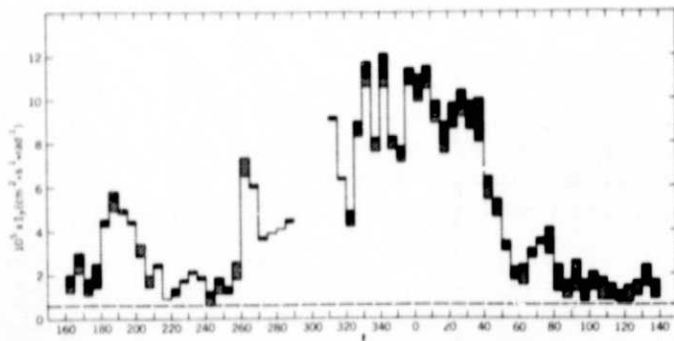
The latitude variation of the intensity I_γ averaged over $60°$ in longitude, has been given by Fichtel et al. (1975) for the center and anti-center of the Galaxy. The data are reproduced in figure 2, a and b, along with the total hydrogen column density, N_H, deduced from an interstellar reddening compilation (Fitzgerald 1968) through equation 1, and averaged in the same longitude range; the corresponding column densities obtained from 21-cm emission, N_{HI}, taken from Daltabuit and Meyer (1970) are also represented. Inspection of the figure suggests the following comments: at latitudes larger than $15°$ where the regions observed are expected to contain cosmic rays with the same intensity as the intensity observed in the solar vicinity, there is a very good agreement between the column density derived from reddening and γ-ray data. The atomic hydrogen seen in 21 cm is seen to be only a fraction of the total density where molecular clouds are known to be important: at low latitudes in the direction of the inner galaxy and in regions connected with Gould's belt. The difference between the column density derived from reddening data at low latitudes show that the cosmic ray intensity must increase in the inner galaxy by about a factor of 2 on the average (a similar conclusion has been reached by Stecker et al. 1975 and Bignami et al. 1975) and decrease outside the solar circle as already noted by Dodds et al. 1975. Finally, it must be noted that the $\pi°$ production in the Galactic plane at high latitudes contributes a flux $I_\gamma = 4 \times 10^{-6}$ ph cm^{-2} s^{-1}sr^{-1} at the poles, which cannot be neglected when assessing the intensity of an extragalactic isotropic background.

The conclusion which is new and relevant to our purpose here is that the proportionality between the γ-ray intensity I_γ and the interstellar reddening E_{B-V}, expressed by equation 3, is well confirmed by the presently available latitude distribution of γ-ray where the cosmic ray density is believed to be uniform. We are thus confident that it can be used to take into account the small scale distribution of the closeby interstellar medium and deduce its contribution to the γ-ray distribution.
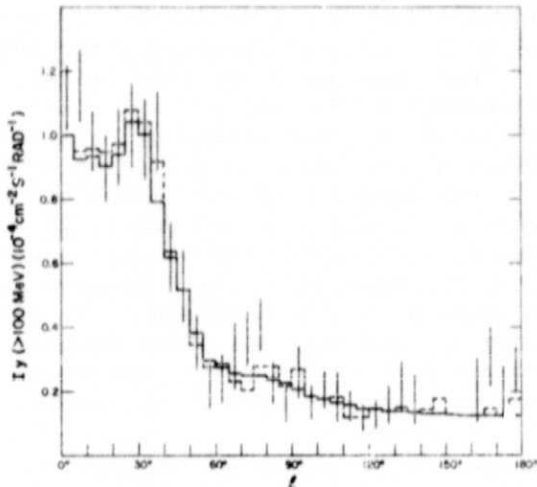
The patchiness of closeby features along with the finite angular resolution of γ-ray detectors may to some extent mimic the presence of sources, which have first been associated with molecular clouds by Black and Fazio (1973). It can also be noted that the column density of the core of dense molecular clouds is comparable to the column density to the Galactic Center, and they would stand up as bright spots ($I_\gamma \approx 10^{-3}$ ph cm^{-2} s^{-1} sr^{-1}) if the angular resolution of the detector were high enough, that is better than $1/2°$. The likelihood of the existence of γ-ray source-like excesses has been recently discussed by Serra and Niel (1975).

Figure 3. γ-ray distribution as a function of galactic longitude, summed up in a b = $\pm$ $10°$ strip. Outer contour: original SAS II data from Fichtel et al. (1975). Black area: predicted contribution from the interstellar medium within 0.5 kpc of the sun, as deduced from interstellar reddening and equation 1. Shaded area: contribution of the interstellar medium between 0.5 and 1 kpc of the sun.

The reddening data in the strip $\Delta b = \pm 10^\circ$, shown in figure 1b, have been used to predict the contribution of nearby features to the γ-ray intensity I_γ, through equation 3. The contribution of matter within 0.5 kpc of the sun (black area) and from 0.5 to 1 kpc (dashed area) are represented in Figure 3 superimposed on the original profile obtained by Fichtel et al. (1975) from the SAS II data. Similarily, in Figure 4, the longitude distribution computed by Stecker (1975) from CO data (solid line) and the same after correction for local features (dashed line) are reproduced. The fit is obviously improved, and an analysis of the details of the γ-ray structure is quite appealing. Note that the corrections generally go in the right direction, in spite of a trend to be slightly too weak.

Figure 4. The gamma-ray distribution at positive galactic longitude as obtained by Stecker (1975) (solid line), as corrected for nearly contributions (this work, dashed line) and the carbon monoxide distribution (Scoville and Solomon 1975). Note the improvement of the agreement between CO data and γ-ray distribution when corrected for nearby contributions.

The blank area which is left in Fig. 3 now represents the γ-ray emission profile produced by the large scale features, allowing a discussion of galactic structure. A peak at the Galactic Center, with a width of order 15° (or ~ 2 kpc), clearly stands up and may be associated with inverse Compton emission (Dodds et al. 1975). At $\ell \approx 30^\circ$, a well-defined maximum becomes evident and exactly corresponds to the peak in the longitude distribution of CO (Scoville and Solomon 1975, Burton et al. 1975). It also fits to the profile computed on the basis of a detailed model of the Galaxy (Bignami et al. 1975), and corresponds to the double feature around $\ell \sim 335^\circ$. However, at $\ell \sim 30^\circ$ both arms are too close to be resolved with a 5° resolution. It is interesting to note that the distribution of giant HII regions (Mezger 1970, Wilson et al. 1970) exhibit a very similar overall property but with a more detailed structure. Finally, in the region $80^\circ < \ell < 140^\circ$, the contribution from the outer Galaxy (beyond $1 \sim 2$ kpc of the sun) seems to be very weak, a conclusion consistent with a sharp roll-off of the cosmic ray density at $R > 12$ kpc. The existence of sharp features in the γ-ray profile indicates that matter have to be located in narrow lanes at the inner edge of the spiral arms defined from 21 cm measurements. Similarly, narrow dust lanes (obviously associated to molecular clouds in our Galaxy) are observed along arms in external galaxies (Lynds 1975). The radial distribution of matter deduced through unfolding of the longitude distributions implies a rapid roll off of the density of the lanes along the spiral arms as they wind out starting at ~ 4 kpc. Such a picture is in agreement with the model developed by Roberts (1974) for spiral structure.

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ON THE ORIGIN OF COSMIC RAYS

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Using recent surveys of molecular clouds and γ-rays in the
galaxy, it has become possible to determine the distribution
of 1 to 10 GeV cosmic-ray nucleons in the galaxy. This
distribution appears to be identical to the supernova
remnant distribution to within experimental error, providing
strong support for the hypothesis that supernovae produce
most of the observed cosmic rays. This distribution resembles
that of OB associations of average age ∼30 million years
suggesting that cosmic rays are produced by population I
objects about 30 million years after their birth.

The problem of the origin of cosmic rays has been the central problem of
high energy astrophysics for over a generation (see, e.g., Shapiro 1962, Ginzburg
and Syrovatskii 1964, Rosen 1969, and Brecher and Burbidge 1972).

Shortly after the discovery of the 3K microwave blackbody background radiation,
it was first noted by Fazio, Stecker and Wright (1966) that such radiation precluded
the existence of cosmic-ray electrons outside the galaxy with the same intensity
as that observed locally. They noted that such electrons would produce more 100
MeV γ-rays than observed if their distribution extended more than ∼30 kpc from
the earth. Thus, it became apparent that cosmic-ray electrons were of galactic
origin.

It was further noted by Greisen (1966) and Zatsepin and Kuz'min (1966) that
the blackbody background radiation would interact with ultrahigh energy cosmic rays
of extragalactic origin to produce a cutoff in their energy spectrum. The lack of
an observed cutoff allowed one to rule out the universal origin hypothesis for
ultrahigh energy cosmic rays and to place limits on the extent of their source
region as being within 300 Mpc (Stecker 1968). Galactic origin of even ultrahigh
energy cosmic rays has been advocated (Stecker 1971, Syrovatskii 1971) and support
of this hypothesis has been recently provided by indications of the anisotropy
of ultrahigh energy cosmic rays (Krasilnokov et al. 1974, Hillas and Ouldridge 1975).

Attempts to place limits on the extragalactic cosmic-ray flux using the γ-ray
background observations have not been conclusive. They still allow a universal
cosmic-ray nucleon flux provided the mean intergalactic gas density $n_{IG} \leq 10^{-7} cm^{-3}$
and allow origin within the local supercluster even if $n_{IG} \approx 10^{-5} cm^{-3}$ (Stecker 1975).
Thus, the discussion of the extragalactic versus galactic origin hypothesis has
continued down to the present (Brecher and Burbidge 1972, Ginzburg 1974).

It has long been realized that observations of galactic γ-rays could provide
important information for resolving this problem, but until now it has not been
possible because of insufficient γ-ray data and an incomplete knowledge of the
amount and distribution of an important component of the interstellar gas, viz.,
molecular hydrogen. Recent observations of the large-scale galactic distribution
of γ-radiation (Fichtel et al. 1975) and molecular clouds (Scoville and Solomon 1975)
have now made it possible to investigate the large-scale distribution of galactic
cosmic rays. Using the new observations, Stecker et al. (1975) have determined

that the cosmic-ray distribution in the galaxy is not uniform as would be indicated by the extragalactic origin hypothesis. These results indicated that there is a weak correlation of the cosmic-ray flux with gas density' (mostly H_2 clouds) in the inner part of the galaxy. Also apparent was a falloff of the cosmic-ray flux in the outer galaxy (also found by Dodds, et al. 1975). The striking similarity between the cosmic-ray distribution deduced by Stecker et al. (1975) and the supernova distribution in the galaxy (Ilovaisky and Lequeux 1972, Kodaira 1975) provides new evidence that supernovae produce the bulk of the cosmic-ray flux.

The galactic γ-rays are primarily the result of the decay of π^0-mesons produced in cosmic-ray interactions with interstellar gas (Kniffen et al. 1973). Their flux is therefore proportional to the product of gas density and cosmic-ray intensity integrated along the line-of-sight within the solid angle subtended by the γ-ray telescope. If a cosmic-ray flux distribution is assumed and Compton and bremsstrahlung γ-rays are also included in the calculation (a 30 percent correction at most), one can calculate the flux expected to be observed by the SAS-2 γ-ray telescope of Fichtel et al. (1975) integrated over $+10^0$ in galactic latitude and averaged over 5^0 longitude. This can only be done over the half of the galaxy for which the molecular cloud distribution has been determined (Scoville and Solomon 1975). The details of this calculation are given by Stecker et al. (1975). They found that a uniform cosmic-ray flux distribution leads to a γ-ray flux which is a factor of $\sim$2 too high compared to the observations in the anticenter direction and which is too low in the direction of the galactic center.

Using the same methods, a calculation of the γ-ray flux distribution can also be made under the assumption that the cosmic-ray distribution is proportional to the supernova remnant distribution in the galaxy, as would be expected if (1) supernovae are the principal source of cosmic rays, and (2) cosmic rays
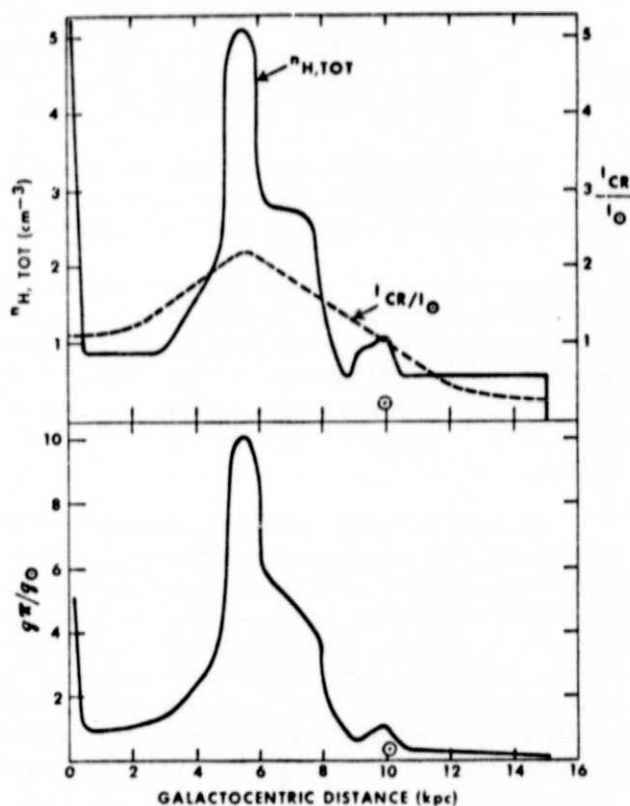

Figure 1. (a) (top) Galactic distributions of cosmic-ray intensity using the supernova remnant distribution of Kodaira (1974) and total gas density deduced by Stecker et al. (1975).

(b) (bottom) Distribution of π^0 production rate in the galaxy based on (a).

diffuse only a few hundred parsecs before leaking out of the galactic disk (Jokipii and Parker 1969, Ramaty, Reames and Lingenfelter 1970).

Using the supernova distribution obtained by Kodaira (1974) as representative of the galactic cosmic-ray flux distribution (normalized so $I_{CR}/I_{\odot} = 1$ at 10 kpc), the longitude distribution of γ-rays as would be observed by the SAS-2 telescope has been calculated. Figure 1a shows the cosmic-ray and total matter distributions used (see Stecker et al). Figure 1b shows the calculated γ-ray emissivity from π^{0}-decay. The results are shown by the histogram in Figure 2 along with the data actually obtained by Fichtel et al. (1975), indicated by the vertical lines. The calculated distribution is in remarkable agreement with the data, providing strong support for the hypothesis that supernovae produce most of the observed cosmic rays.
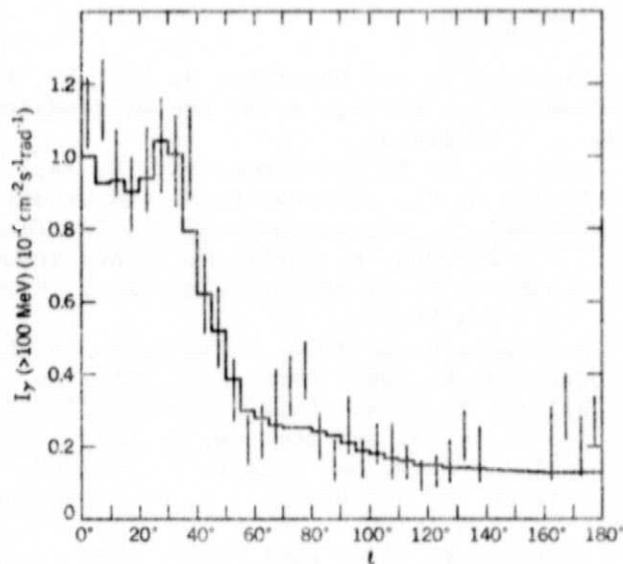

Figure 2. Calculated longitude distribution of galactic γ-rays under the supernova origin hypothesis (histogram) compared with the observations of Fichtel et al. (1975) (vertical lines).

The supernova remnant distribution used here can be correlated with the distributions of various other population I objects to estimate the average age of the remnants. For this purpose, we turn to the detailed discussion of the correlation of gas and OB associations made recently regarding M31 (Emerson 1974). These results show that the surface densities of HII regions and atomic hydrogen (HI) are related by $\sigma_{HII} \propto (\sigma_{HI})^{2.23}$. For our own galaxy, due in part to optical depth effects, the HI distribution obtained from 21 cm observations may be to some extent misleading in the inner galaxy (Scoville and Solomon 1975, Stecker et al. 1975). However, using the data of Mezger (1970) we find a correlation between the supernova remnant distribution and the HII region distribution of the form $\sigma_{SN} \propto (\sigma_{HII})^{0.4}$. Assuming, as for M31, $\sigma_{HII} \propto (\sigma_{HI})^{2.23}$, it then follows that $\sigma_{SN} \propto (\sigma_{HI})^{0.89}$. If the correlation between OB associations and HI gas is also expressed in the form $\sigma_{OB} \propto (\sigma_{HI})^{m}$, it is found that the older the association, the smaller the value of m (Emerson 1974). The decrease of this correlation with age is generally attributed to a spreading out of the stars in the OB associations with time, all the stars in the association having been spawned from the same cloud complex. The correlation defined by m = 0.89 is close to the mean correlation with gas of all OB associations and consistent with an age of 3×10^{7} yr. Thus, it appears that the sources of galactic cosmic rays are young galactic population I objects, most likely to be supernovae.

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THE INTERACTIONS OF ULTRAHIGH ENERGY COSMIC RAY NUCLEI WITH INTERGALACTIC

PHOTON FIELDS: RELATION BETWEEN MEAN ATOMIC MASS, AGE, AND ORIGIN

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We present some results of detailed Monte Carlo calculations of
the interactions between ultrahigh energy cosmic-ray nuclei and
intergalactic radiation fields using improved estimations of
these radiation fields and recent experimental determinations
of cross sections for single and multiple photodisintegrations as
a function of energy for $1 \leq A \leq 56$. Starting from Fe, disintegra-
tion product distributions are determined as a function of time.
Some of these results and their possible astrophysical implications
are discussed here.

1. Introduction. Of the various photon-nucleus interactions possible between
low-energy intergalactic photon fields and ultrahigh energy cosmic-ray nuclei,
the only two of astrophysical significance for attenuation by energy loss in the
10^{18}-10^{21} eV range are pair production and photodisintegration. The physics of
pair production is well determined, and an excellent discussion of the relevant
cross section formulas has been given by Blumenthal (1970) which we have
adopted in our calculations. The photodisintegration process is not as easy
to treat and most previous cosmic-ray papers have used only simple estimations
of the cross section for this process (Gerasimova and Rozental', 1962; Greisen,
1966; Zatsepin and Kuz'min, 1966; Berezinskii and Zatsepin, 1971; and Tkaczyk
et al., in press).

Stecker (1969) used a detailed study (Gorbunov 1968) of the breakup of
^{4}He to determine the lifetime of ^{4}He and ^{56}Fe against one nucleon loss by
interactions with the universal blackbody radiation. The present paper presents
some of the results of a new and much more detailed calculation of intergalactic
photodisintegration of ultrahigh energy nuclei with the following improvements:

1) Use of detailed empirically determined cross section data as a function
of energy for all nuclei with $1 \leq A \leq 56$. (Heavier nuclei are considered too
rare to be of significance in the present context).

2) Use of cross section data for $1 \leq A \leq 56$ for multinucleon disintegrations
as well as single nucleon losses for all cms energies up to ~140 MeV (the π
production threshold).

3) Use of new estimates of the intergalactic infrared radiation field
whose effect is included along with that of the blackbody radiation.

4) Inclusion of energy loss by pair production as well as photodisintegra-
tion in the calculation.

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5) Use of numerical Monte Carlo techniques in order to take proper account of multinucleon loss channels to determine the probability distribution of photo-disintegration histories of nuclei as a function of time.

2. Calculations. The rate for photodisintegration of a nucleus of mass A with the release of N nucleons is given by (Stecker 1969)

$$R_{A,N} = \frac{1}{2} \gamma_A^{-2} \int_0^\infty d\epsilon \, \frac{n(\epsilon)}{\epsilon^2} \int_0^{2\gamma A \epsilon} d\epsilon' \epsilon' \sigma_{A,N}(\epsilon') \tag{1}$$

where $n(\epsilon)$ is the photon density of the background radiation with energy ϵ in the observer's system.

While one and two nucleon losses are dominated, for the most part, by the giant resonance in the photonucleon cross section up to a cms energy ϵ' of ~30 MeV, cross sections for N > 2 become important for A > 10 and ϵ' > 30 MeV. For A = 9, the disintegration is dominated by the reaction

$$\gamma + {}^9Be \rightarrow 2\alpha + n \tag{2}$$

The background radiation is assumed to consist of three components:

1) the blackbody radiation at $T = 2.7$ K;

2) a dilute optical blackbody field at $T = 5000$ K with a dilution factor of 1.2×10^{-15}; and

3) a power-law infrared radiation field estimated from the contributions of extragalactic strong infrared sources such as quasars and Seyfert galaxies. Two power-law forms were considered as probable upper and lower limits for the extragalactic infrared radiation based on cosmological models involving the evolution of extragalactic infrared sources. These power-law photon spectra, which were taken to extend from the optical graybody field to the microwave blackbody field, are given by:

High Infrared: $n(\epsilon) = 1.1 \times 10^{-3} \epsilon_{eV}^{-2.5}$
(HIR)

$(cm^{-3} \, eV^{-1})$

Low Infrared: $n(\epsilon) = 2.6 \times 10^{-3} \epsilon_{eV}^{-2}$
(LIR)

both taken over the range $2 \times 10^{-3} \le \epsilon \le 0.83$ eV.

3. Results. Figure 1 shows the calculated loss time (inverse loss rate) for ${}^{56}Fe$, ${}^9Be$ and ${}^4He$ as a function of Lorentz factor γ for the HIR (solid line) and LIR (broken line) cases. The effects of the differing shapes of $\sigma(\epsilon')$ can be seen as well as the significant difference in rates between the HIR and LIR cases (almost a factor of 10 for ${}^{56}Fe$ with $\gamma \sim 3 \times 10^9$). Also shown are some partial channels for these nuclei so that the effect of multinucleon channels on the total Fe lifetime can be seen as well as the shape of the 2 nucleon contribution to the lifetime of He.

The calculated history of a beam of Fe nuclei starting at two given energies $E_0 = AM_N \gamma_0$ for the HIR case are shown in Figure 2. Shown for comparison are the lifetimes for Fe against one nucleon loss at each γ_0. It is obvious that the lifetimes for complete disintegration are considerably higher (a factor of ~200 for the HIR case).

The gap in the distribution for $5 \leq A \leq 8$ is caused by reaction (2). The Monte Carlo calculations yielded the mean mass A and spread in mass (defined as a standard deviation from the mean) of the products of Fe disintegration as a function of time. Some results are shown in figure 3 for three values of γ_0.

The shaded areas for two of the curves illustrate the standard deviation spread in mass values. These three curves illustrate the time evolution of Fe nuclei for the three basic energy regions where the physics is somewhat different. In the energy range $\gamma_0 \gtrsim 5 \times 10^9$, the energy loss is dominated by photo-disintegration reaction with the 2.7 K blackbody radiation. In that case, the two curves corresponding to HIR

Figure 1. Total nucleon loss times for ^{4}He, ^{9}Be and ^{56}Fe including the effect of multinucleon channels. Two partial loss times are also shown. Solid lines: HIR case, Broken lines: LIR case.

and LIR are the same. In the range $10^9 \leq \gamma_0 \leq 5 \times 10^9$ pair production losses play a role in decreasing γ and therefore decreasing the fragmentation rate (see figure 1) so that the fragmentation time is somewhat longer and the curve is flatter. In the range $\gamma < 10^9$ pair production is again unimportant.

The combined effects of photodisintegration and pair production lead to attenuation of nuclei above a critical observed total energy as given for the six cases shown in table 1. Shown for comparison, is the critical energy for protons from photomeson losses (Stecker 1968).
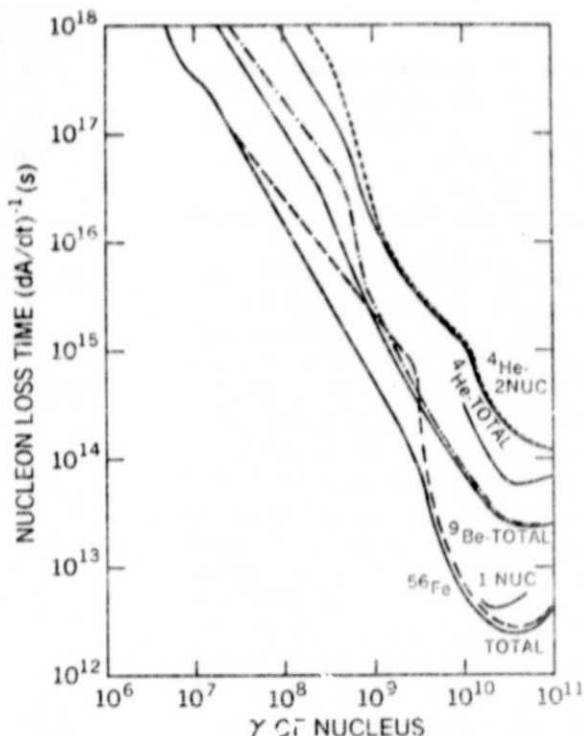
Table 1. Critical Attenuation Energy

	Universal Origin ($t = 4 \times 10^{17}$s)	Supercluster Origin ($t = 10^{15}$s)
HIR	4×10^{18} eV	1×10^{20} eV
LIR	7×10^{18} eV	2×10^{20} eV
No IR (blackbody only)	4×10^{19} eV	no cutoff
Protons (Photomeson losses)	5.3×10^{19} eV	no cutoff

4

For the universal origin case, note that the presence of an infrared   photon field reduces the critical energy by as much as an order of magnitude below what would be expected from the 2.7 K blackbody radiation alone. Furthermore, the numbers given in Table 1 are derived for an initial composition of pure Fe. For nuclei of lower initial A , the cutoff will be at a lower energy. The predicted cutoffs for the universal origin case are very sharp. Since the data at present are consistent with a smooth E^{-3} cosmic ray spectrum up to $\sim$ 1 or 2 x 10^{20} eV, these data appear to rule out the universal origin hypothesis for both protons and nuclei but allow supercluster origin as well as galactic origin for protons and nuclei.

Many more results have been obtained which will be discussed elsewhere (Puget, J.L., Stecker, F. W. and Bredekamp, J. J., in preparation).
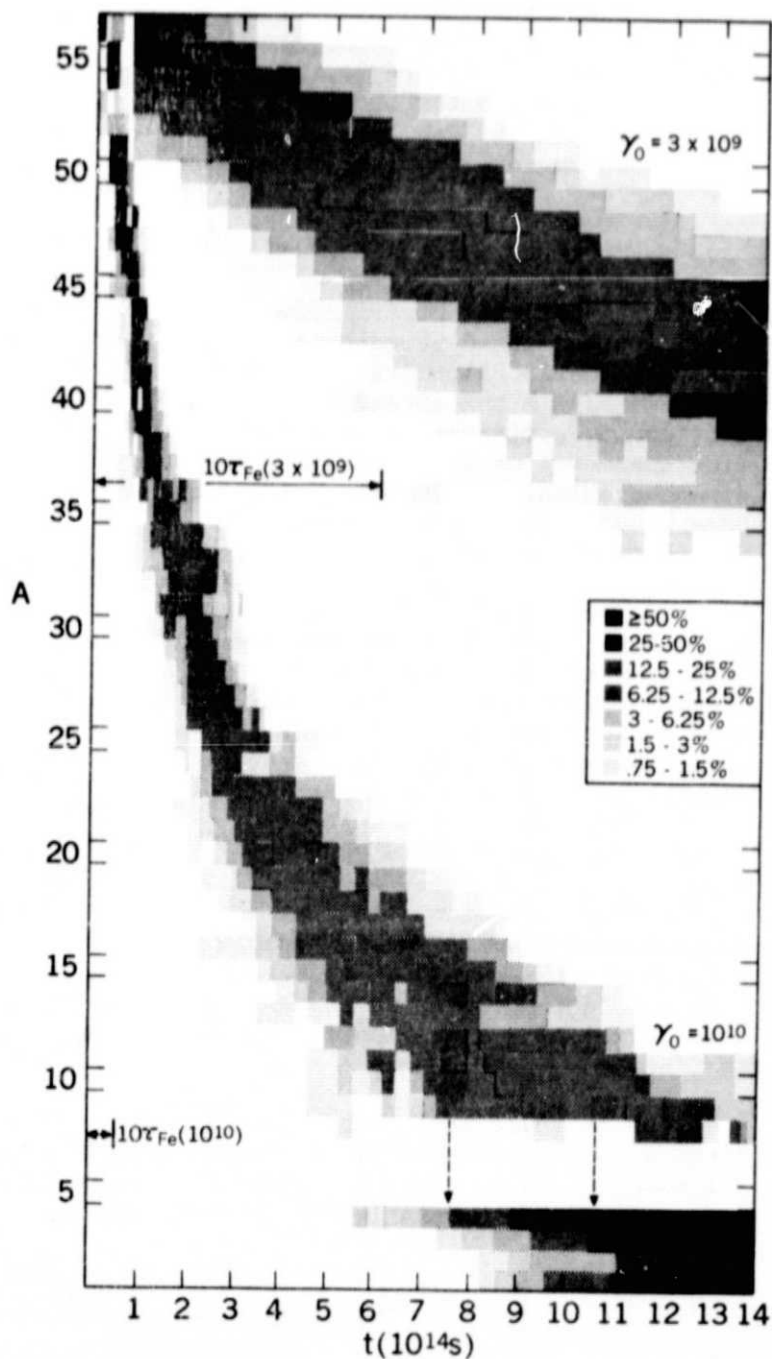

Figure 2. Calculated history of a beam of Fe nuclei with initial energy $AM_N\gamma_o$ for the HIR case for two values of γ_o. Also shown is $10\,\tau_{Fe}(\gamma_o)$ where τ_{Fe} is the lifetime against one nucleon loss (see Figure 1).
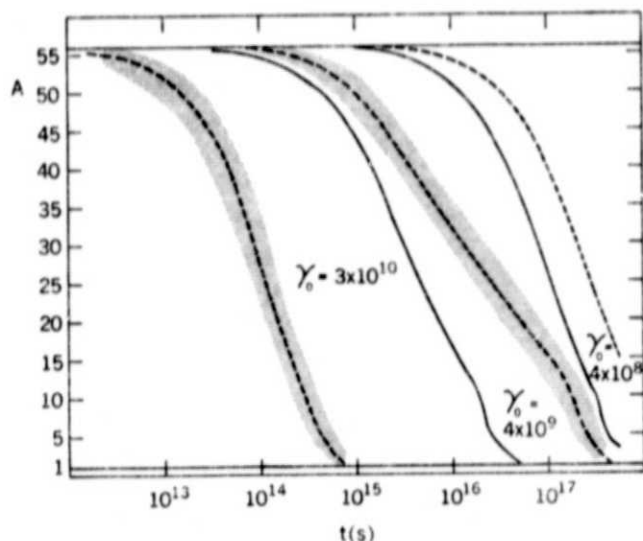
Figure 3. Mean mass A(t) and spread in mass distribution (shaded area) for an initial Fe beam with three values of γ_o. Solid lines: HIR case, Broken lines: LIR case.

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